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Results of Hybrid Photodiode irradiation by 200 MeV protons

Introduction

Hybrid Photodiodes (HPD, [1]) will be used as the photodetector for the Compact Muon Solenoid (CMS) Hadron Calorimeter (HCAL) readout [2]. The HPDs are required to operate in a high radiation environment, where the HCAL detector will receive a total ionizing dose of about 330 rads and a fluence of 4×10^{11} n/cm^2 over a 10 year running period [3]. Effects of HPD irradiation by low energy neutrons were studied and reported previously [1]. In these studies, high energy protons are used to study possible effects of single event burnout [4], since high energy protons are more likely to induce large energy transfer within the HPD silicon. The HPDs were irradiated by 200 MeV protons at the Indiana University Cyclotron Facility [IUCF, 5]. The results of the study are presented below.

Setup

The principles of HPD operation have been described in an earlier note [6]. The HPD schematic view is shown in Fig. 1. The input fiber-optic glass window thickness is 5 mm. A photocathode (PC) is deposited on the internal surface of the window in a sealed vacuum area. The distance between the PC and the silicon (Si) is 3.35 mm +/- 0.02 mm for the HPD. The HPD silicon thickness is 200 μm and the sensitive area diameter is 25 mm. Fig. 2 shows the positioning of the 73 pixels in the HPD. The flat-to-flat distance of the hexagon shaped pixel is 2.8 mm.

The HPD was positioned on a moveable table to simplify its alignment in the beam. The proton beam incidence was normal to the optical window and to the silicon of the HPD. The setup is shown in Fig. 3. For these studies, the beam flux was 5×10^7 protons/cm^2/s. The non-uniformity of the beam intensity across the HPD sensitive area was less than 20%. The signals were taken from the central pixel, number 37, only. The remaining pixels were grounded. The signal from pixel 37 was amplified by factors of 30 and 300 using two amplifiers. A QVT module was used to analyze the HPD signal spectra. A Tektronix TDS 3054, 500 MHz digital oscilloscope was used to observe and register the HPD signals. The HPD bias current was measured by a TENMA digital multimeter, model number - 72-6202. A schematic view of the apparatus is shown in Fig. 4.

Measurements

The HPD's functionality was tested before and after irradiation. The test was performed in the pulse mode. A voltage pulse from an AV-1000-C pulse generator drove a light emitting diode (LED, Nichia NSPG500S) equipped with a 1 mm diameter 1 meter long optical fiber that was used to transport light from the LED to the HPD's pixels. The tests included, but were not limited to, gain curve measurements and signal versus bias voltage dependence. These measurements were performed in the linear operating range of the HPD.

Two 73 pixel HPDs were tested in the beam. One HPD had no photocathode (S/N AL 0051003, with broken vacuum); the other HPD was a totally functional device (S/N AY 0128122). Initial tests were made with the AL 0051003. Bias voltage settings of 100V, 150V, and 200V were used. The AY 0128122 was measured with a 200V bias voltage only, with and without an 8kV high voltage applied. The total collected dose was about 10^{11} protons/cm^2 for each data set. Clear signals from the HPDs were seen only when the beam was on. Fig. 5 shows a typical amplified signal with a gain of 30. The signal shape was determined by the amplifier's timing parameters not by the intrinsic speed of the HPD. The bias current was monitored during all data taking. The dependences of the current on the accumulated dose is shown in Fig. 6. These data correspond to the measured current with the beam turned off.

Discussion

No single event burnout effects were observed during our irradiation studies, where a dose equivalent to more than 10 years of operation in the CMS environment was achieved. The HPD leakage current, however, did increase after irradiation. The current of the HPD AL0051003 (with broken vacuum) increased from 100 nA (initial dark current value) to 1.22 μA after the first exposure with 200 MeV protons. After 5 months time, just before this second irradiation the current was equal to the post-irradiation measurement therefore no recovery was observed. This suggests that the leakage current increase is due to displacement damage in the silicon rather than from total ionizing dose and is consistent with the neutron studies done previously [2]. The current of the HPD AY 0128122 increased from 80 nA to 2.28 μA after the irradiation. The immediate post-irradiation value decreased to 0.8 μA during the next 2 months after the irradiation indicating something like an annealing effect. This disagreement in the behavior of the two devices makes a final conclusion about post irradiation HPD's behavior impossible. This study should be continued. Nevertheless, the current increase at a rate of 15.5 nA/10^{10} p/cm^2 should not degrade the performance of the HPD.

The typical spectrum observed during irradiation consists predominantly of minimum ionizing particle (MIP) signals corresponding to the 200 MeV protons passing through the silicon of the HPD. It can be described in terms of the electromagnetic interactions of the protons in the thin layer of the silicon and is functionally represented by a Landau-Vavilov distribution with a 0.18 MeV mean energy deposition. This energy deposit corresponds to about 48000 electron-hole pairs produced in the silicon. A threshold of greater than the one MIP signal was set on the QVT in order to measure signals with higher energy deposition. The spectrum of the resulting signals is shown in Fig. 7. These larger signals are due mostly to nuclear interactions of the protons with the silicon. No noticeable difference was observed in the spectra for different bias voltage (100, 150, 200 V) or with the high voltage turned on and off .

Monte Carlo simulations with the MARS 14 code [7, 8] have been performed. A 200 MeV proton beam hits a 5 mm thick optical fiber window followed by a 3.5 mm gap and 0.2 mm silicon layer. The calculated probability of inelastic nuclear reactions is 1.3% in this setup. On average 99.5% of the proton energy deposited in the silicon (0.18 MeV) is due to ionization energy loss. The rest is due to electromagnetic showers induced by knock-on electrons, recoil nuclear products and heavy fragments. The calculated distribution of the deposited energy in the silicon is presented in Fig. 8, 9. The first several decades are a typical Landau – Vavilov distribution. The tail is due to secondary products. It is worth noting that up to 100% of the proton energy can be deposited in the silicon according to the result of the reference [9].

Conclusion

No single event burnout [3] effects were observed in the HPD under 200 MeV proton irradiation. The total accumulated dose corresponds to more than 10 years of the HPD operation at CMS.

The measured spectra of proton energy deposition in the HPD's silicon are in agreement with the Monte Carlo simulation. The spectra mainly consist of two parts: one part is due to the proton ionization of silicon atoms, while the other represents the interaction of protons with the silicon nucleus and has much lower probability.

Acknowledgements

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References

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9. T.Brandt "A Tagged Proton Experiment to Confirm NASA's Model for Evaluating the Risk of Failure in Silicon Off-the Shelf Microelectronic Parts and Systems", undergraduate research program in nuclear physics, the Indiana cyclotron facility, June-August 2000.

Figures Captions.

1. Schematic view of the HPD.
2. HPD Pixel schematic view.
3. Data taking setup.
4. Block diagram of the measurements.
5. Typical amplified HPD signals.
6. The dependence of leakage current on accumulated dose. A – AL 0051003, B – AY 0128122 just after irradiation.
7. Measured spectrum of the signals of HPD irradiated by 200 MeV protons.
8. Monte Carlo spectrum for energy deposition in the HPD's silicon.
9. Monte Carlo spectrum for energy deposition in the HPD's silicon. 5 mm optical fiber window, 3.5 mm gap between photocathode and silicon, 0.2 mm of the silicon are taken in the model.

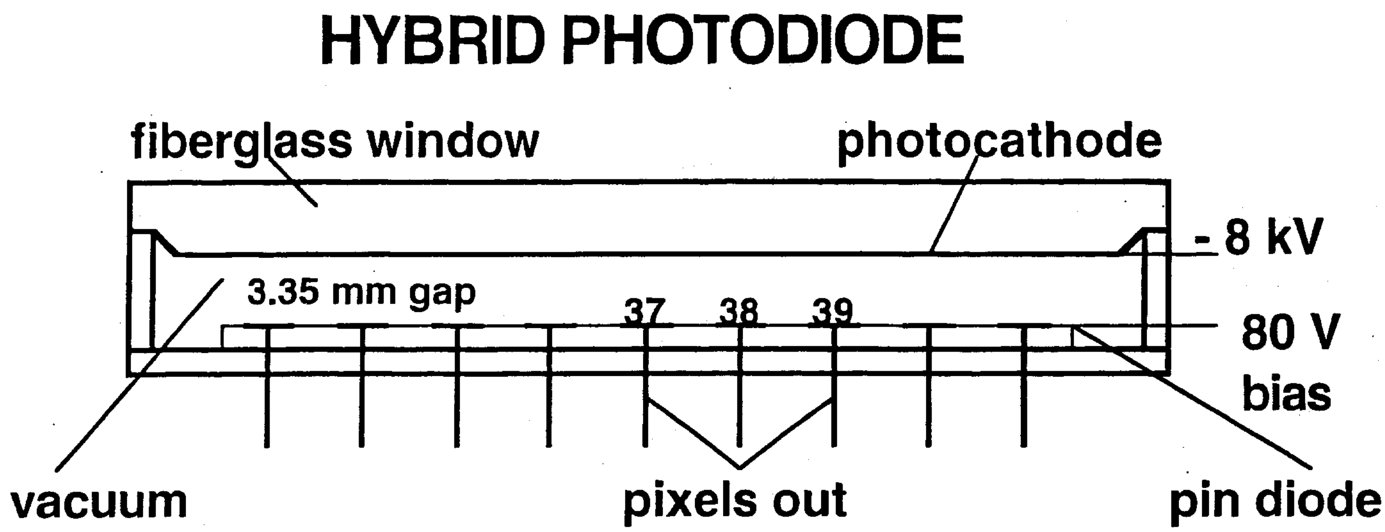
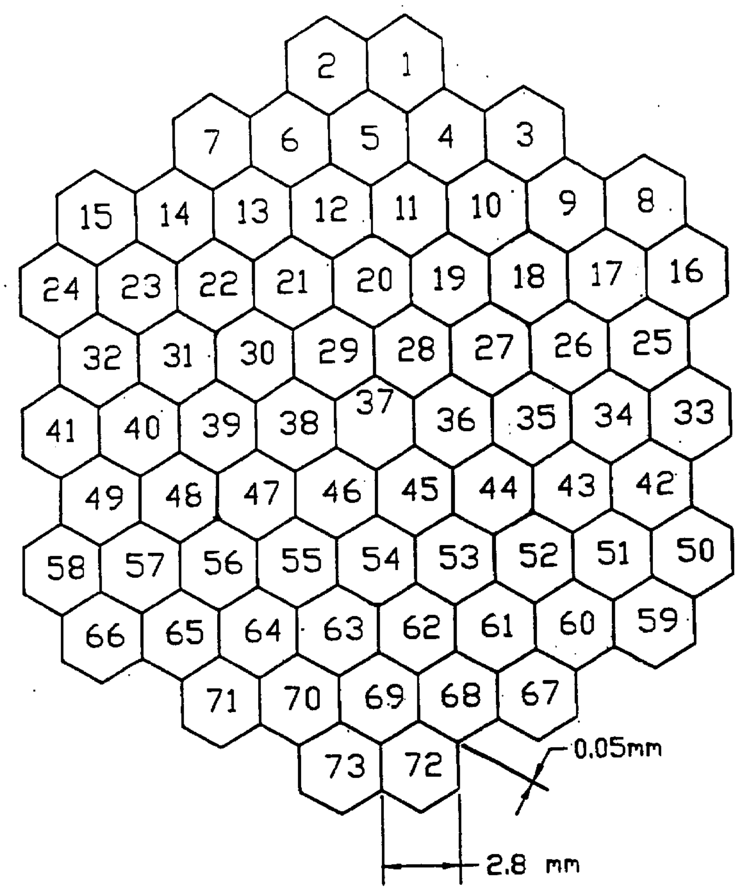

HYBRID PHOTODIODE
fiberglass window
photocathode
- 8 kV
3.35 mm gap
37
38
39
80 V
bias
vacuum
pixels out
pin diode

Fig. 1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55
54
53
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71
70
69
68
67
73
72
0.05mm
2.8 mm

Fig. 2

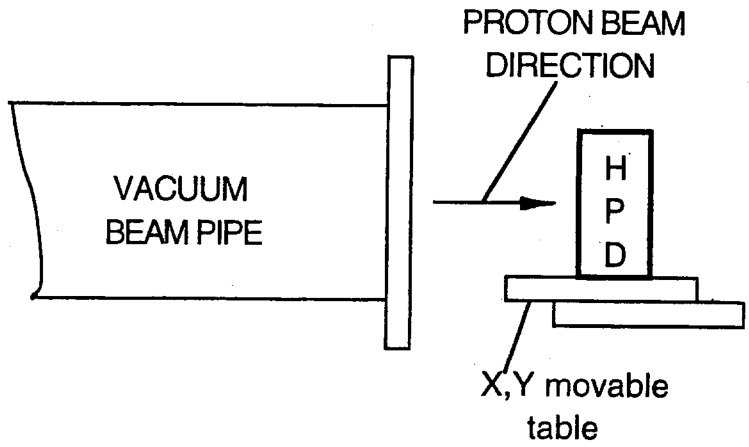

PROTON BEAM
DIRECTION
VACUUM
BEAM PIPE
H
P
D
X,Y movable
table

Fig. 3

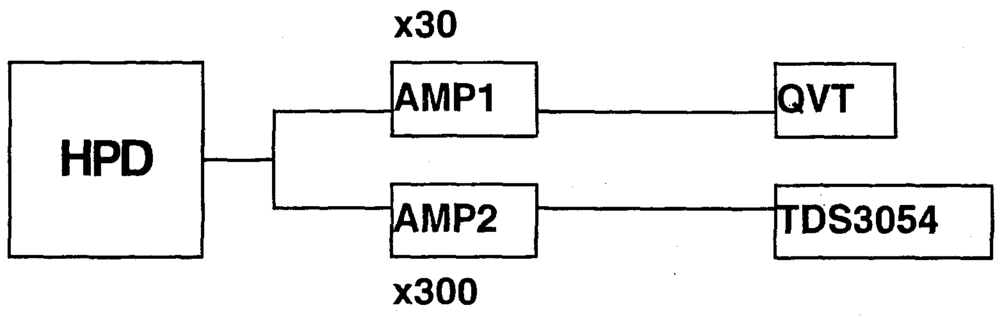
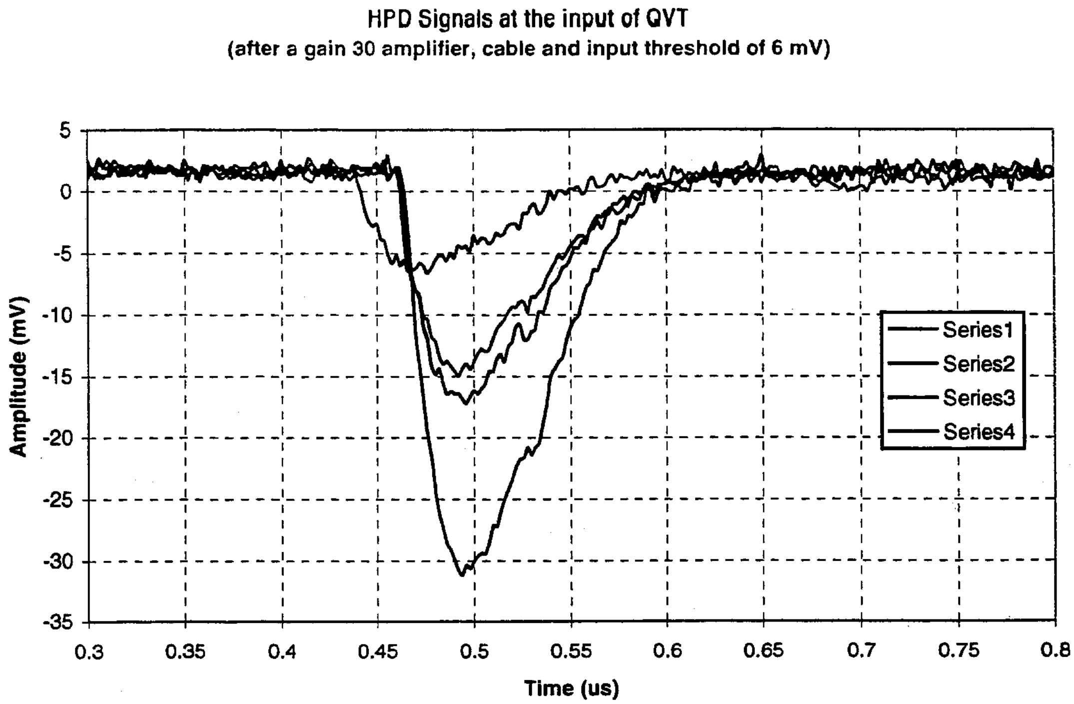


Fig. 4



HPD Signals at the input of QVT
(after a gain 30 amplifier, cable and input threshold of 6 mV)
5
0
-5
-10
-15
-20
-25
-30
-35
Amplitude (mV)
0.3
0.35
0.4
0.45
0.5
0.55
0.6
0.65
0.7
0.75
0.8
Time (us)
Series1
Series2
Series3
Series4

Fig. 5

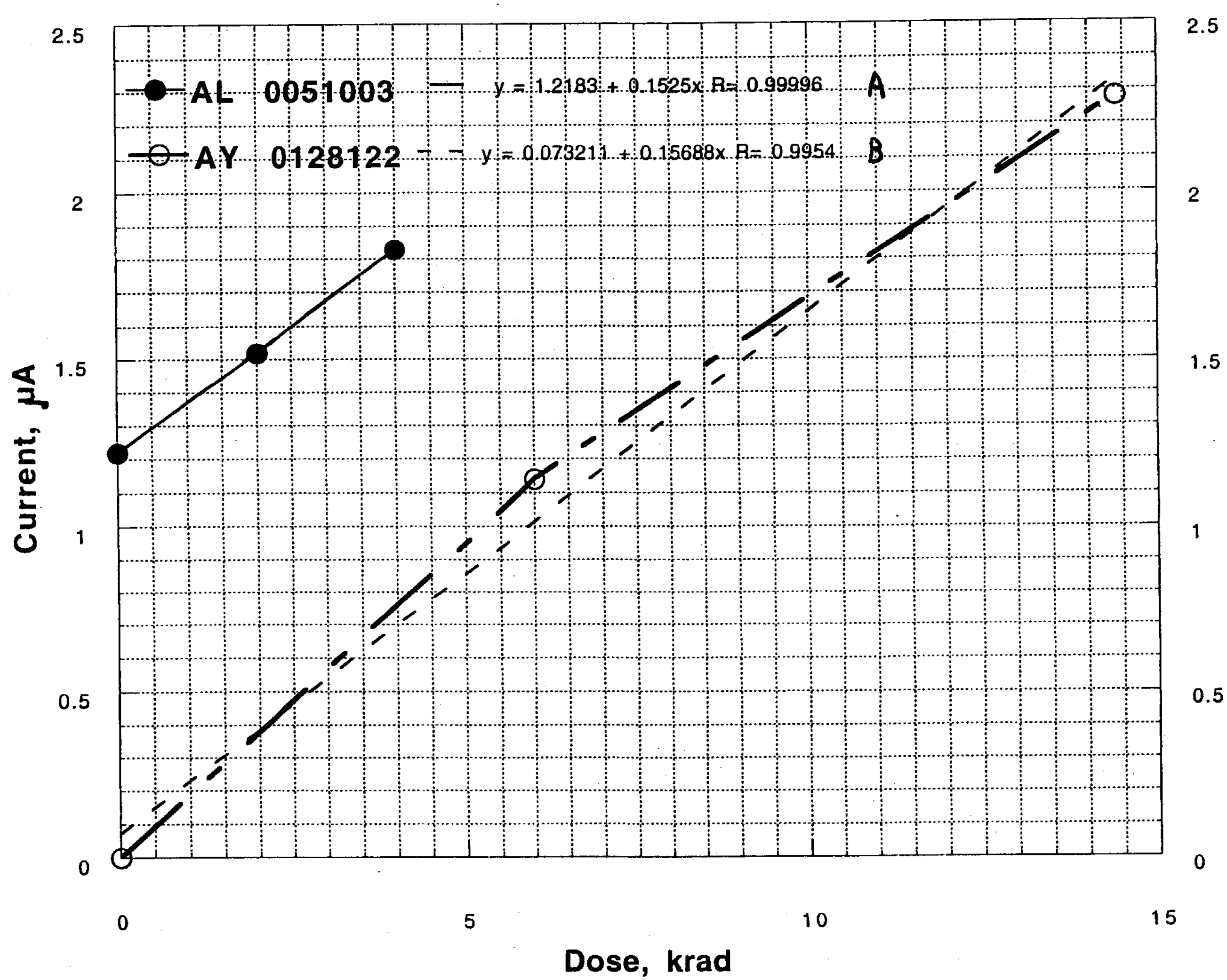

AL 0051003
y = 1.2183 + 0.1525x R= 0.99996
A
AY 0128122
y = 0.073211 + 0.15688x R= 0.9954
B
Current, μA
Dose, krad
0
0.5
1
1.5
2
2.5
0
5
10
15

Fig. 6

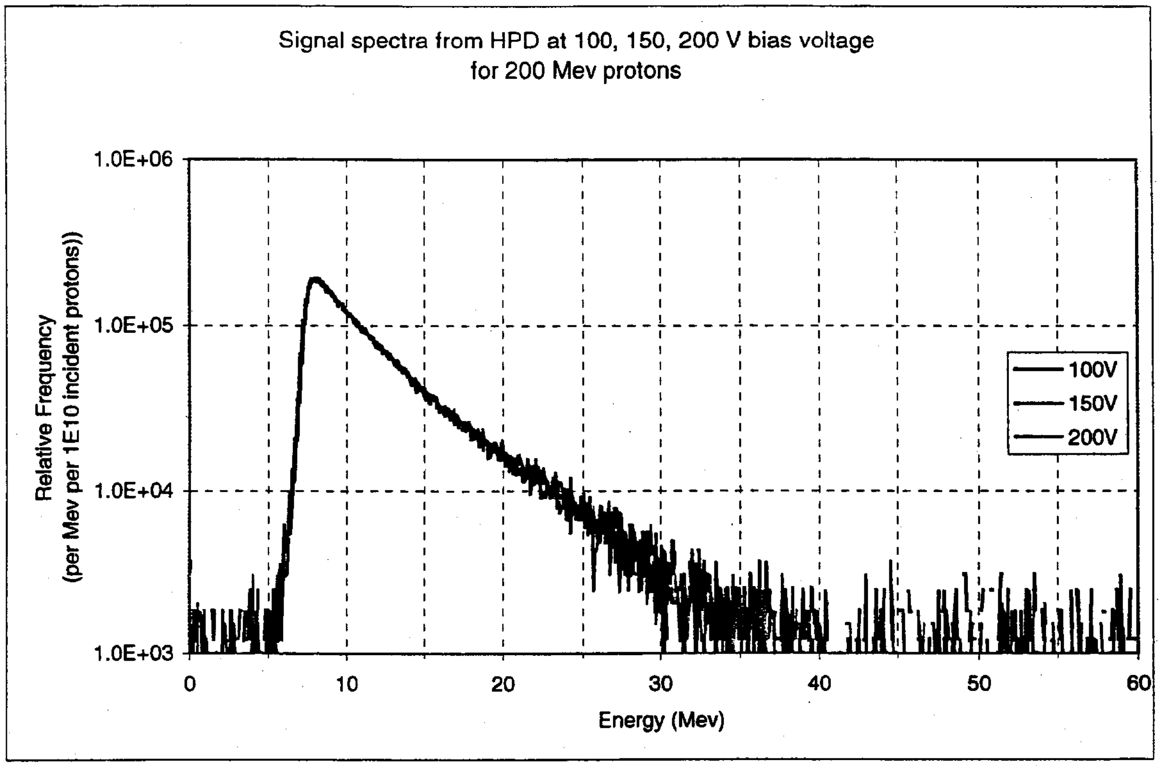
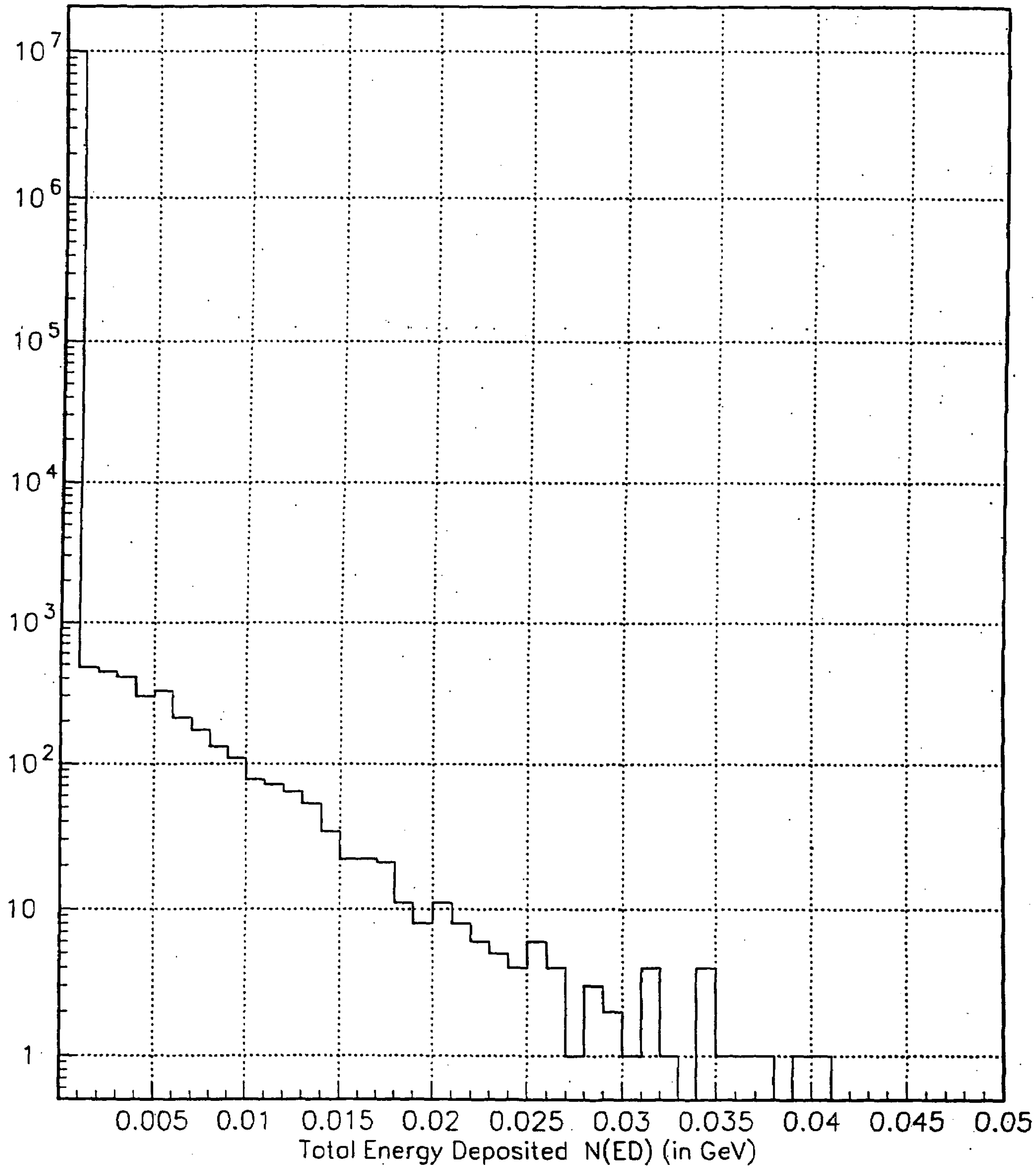

Signal spectra from HPD at 100, 150, 200 V bias voltage
for 200 Mev protons
Relative Frequency
(per Mev per 1E10 incident protons))
1.0E+06
1.0E+05
1.0E+04
1.0E+03
0
10
20
30
40
50
60
Energy (Mev)
100V
150V
200V

Fig. 7



10^7
10^6
10^5
10^4
10^3
10^2
10
1
0.005 0.01 0.015 0.02 0.025 0.03 0.035 0.04 0.045 0.05
Total Energy Deposited N(ED) (in GeV)

Fig. 8

z1/09/04 12.20

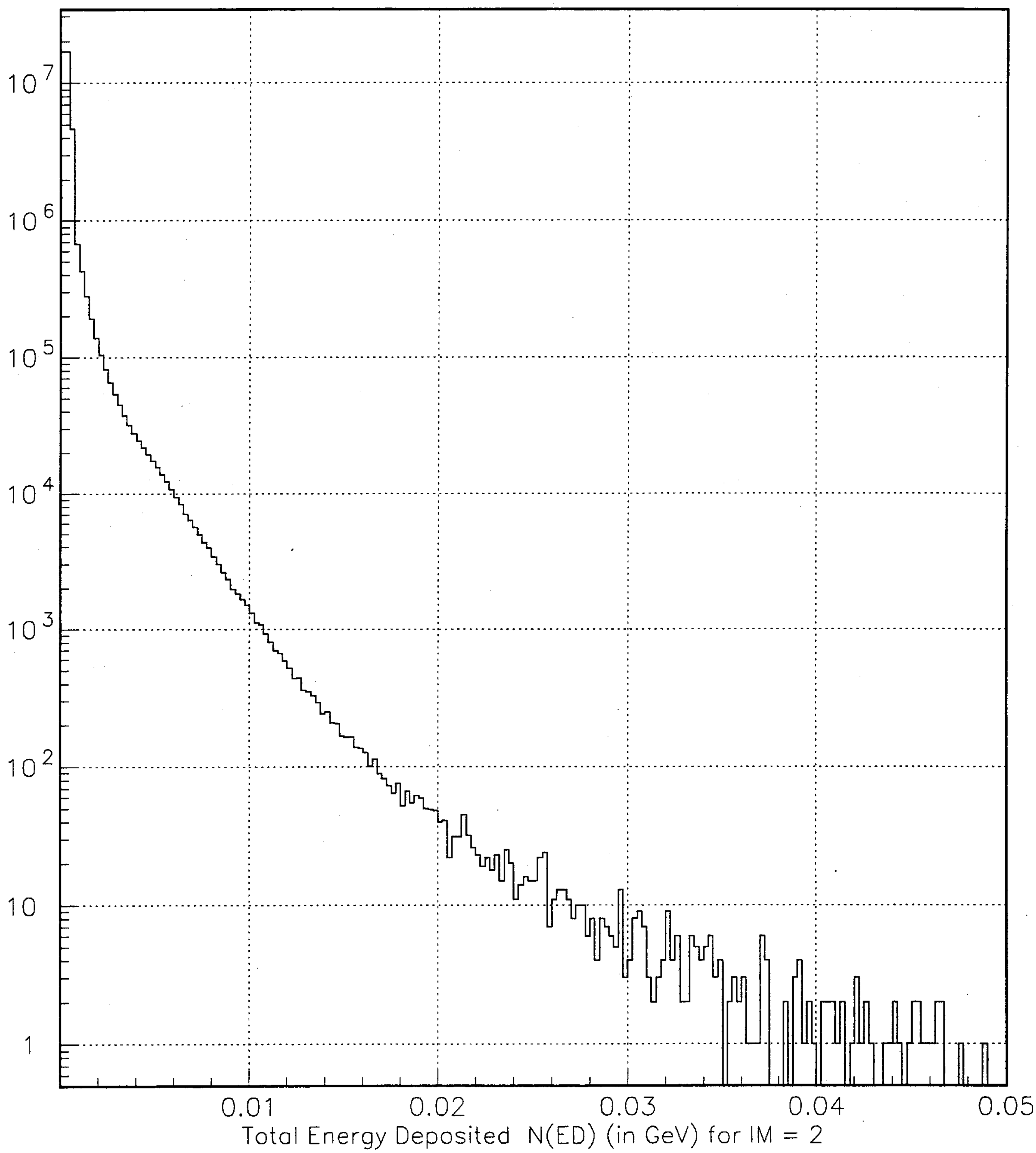


Fig. 9